What radar reveals about crystal orientation: A study from Greenland Ice Sheet

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

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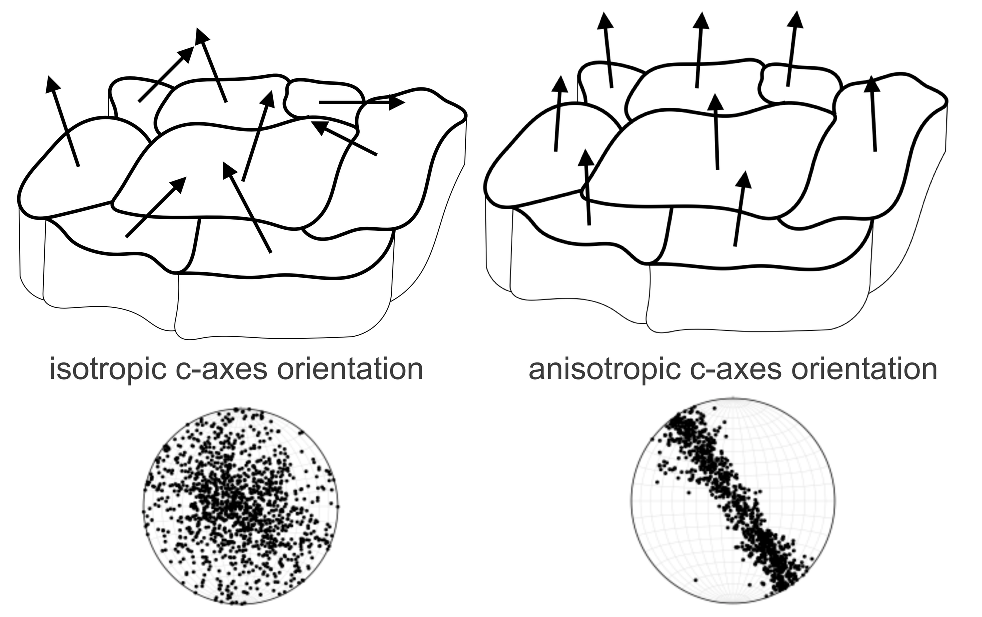
Crystal Orientation



- **c-axis:** describe orientation of ice crystals, different for each grain in polycrystalline ice
- **Crystal Orientation Fabric (COF):** ensemble of different **c-axes**, visualised with Schmidt diagram
- **isotropic COF:** uniform distribution of c-axis orientation
- **anisotropic COF:** oriented distribution of c-axes
- COF is formed by the **stress regime**

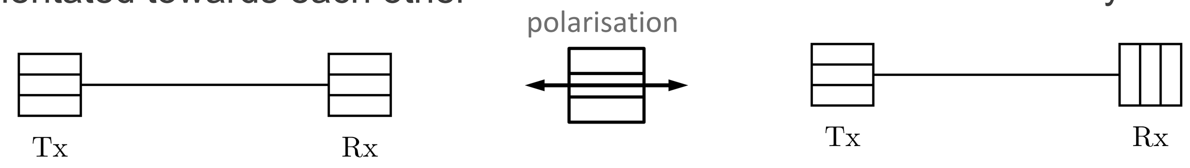
(see Cuffey and Paterson (2010))

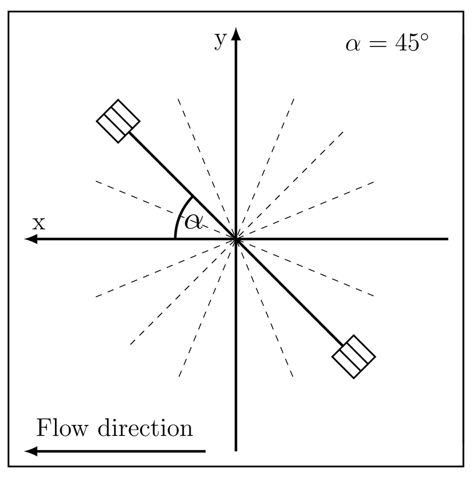
Polarimetric pRES

- phase-sensitive Radio Echo Sounder (pRES) (Nicholls et al. (2015))
- frequency-modulated continous wave (FMCW) radar (200 – 400 MHz)
- Polarimetric pRES (PpRES) measurement procedure:
  1. rotating both antennas in **22.5°** steps around their centre up to 157.5°
  2. using two different antenna orientations:

Horizontal – Horizontal (**HH**): direction of polarization is orientated towards each other

Horizontal – Vertical (**HV**): direction of polarization is rotated by 90°



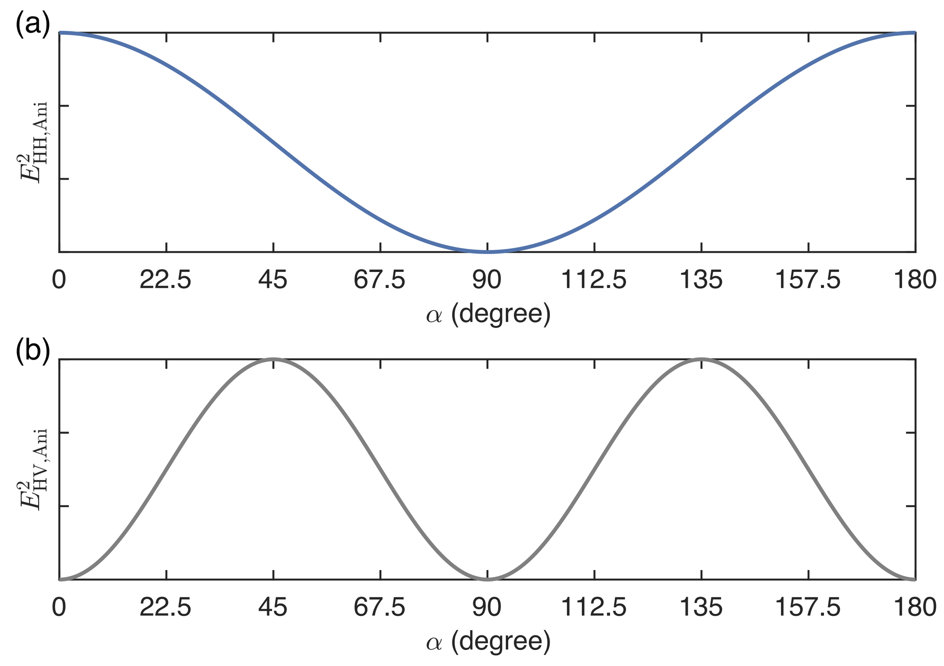


Anisotropy in Radar

Anisotropic Surface

reflections from an anisotropic surface
(surface between **layers of different anisotropic COF**)

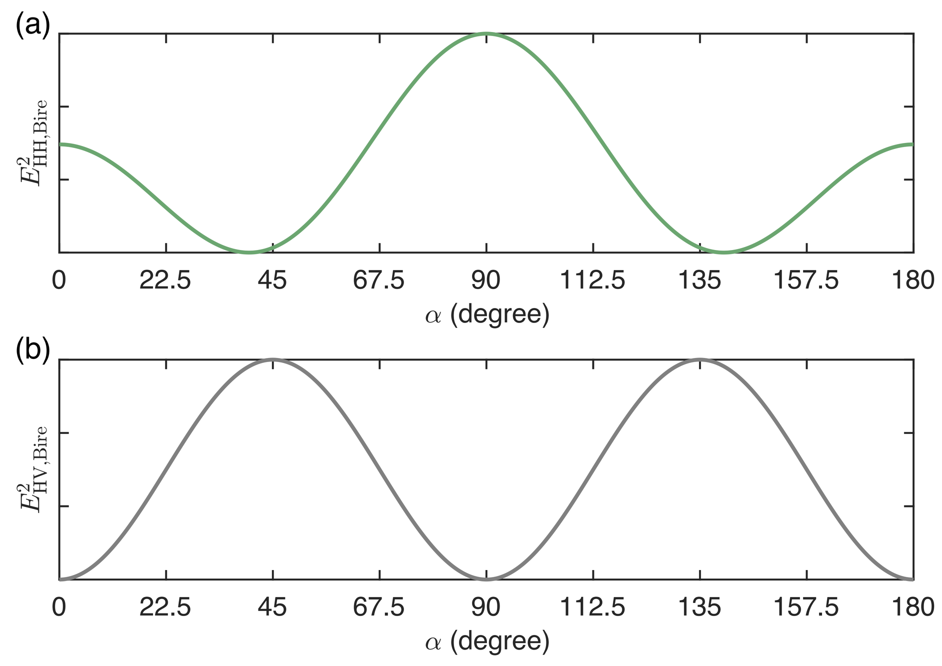
Reflections of a linear polarised wave at an Anisotropic Surface will cause a rotation of the polarisation of an electromagnetic wave. The received amplitude pattern for a HH orientation ($E^2_{HH,Ani}$) consists of one maximum and for a HV orientation ($E^2_{HV,Ani}$) of two maxima for a half circle of 180°.



Birefringent Medium

reflections from within a uniaxial birefringent medium
(medium of spatially **constant anisotropic COF**)

A linear polarised wave penetrating into a birefringent medium is refracted in an ordinary and an extraordinary wave. After this reflection, the received wave is ellipticaly polarised and causes two maxima in the amplitude in HH ($E^2_{HH,Bire}$) and HV ($E^2_{HV,Bire}$) orientation for a half circle of 180°.



Reflections can be caused by changes in **density**, **conductivity** or **COF**. Anisotropic surfaces are always caused by changes in COF.

(see Hargreaves (1977) and Fujita et al. (2006))

East Greenland Ice-Core Project

East Greenland Ice-Core Project (EastGRIP):
Deep ice core in the **North-East Greenland Ice Stream (NEGIS)**

C-axis orientation analysed with **thin sections** and visualised with a **Schmidt diagram.**
Eigenvalues portray c-axis distribution as the three principal axes of an ellipsoid.
EastGRIP: **778 thin sections** down to **1714 m** – more coming

eigenvalues	inertia shape	distribution
$\lambda_1 = \lambda_2 = \lambda_3 = 1/3$	sphere	uniform distribution
$\lambda_1 = \lambda_2 < \lambda_3$	prolate ellipsoid	unimodal cluster
$\lambda_1 < \lambda_2 = \lambda_3$	oblate ellipsoid	girdle fabric

Eichler (2013)

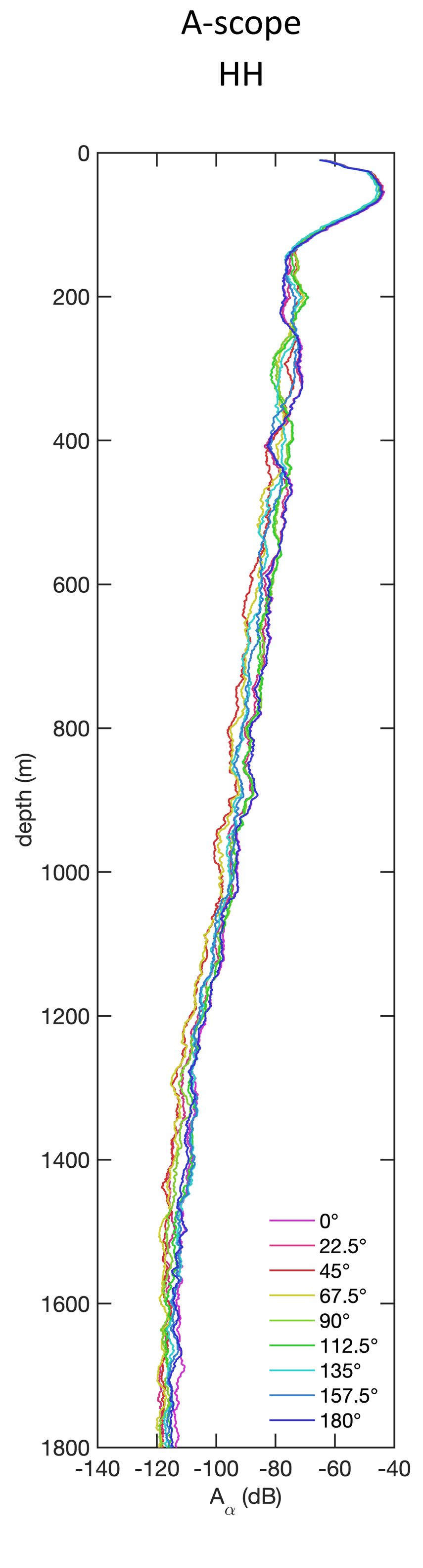
Polarimetric pRES measurements 1 km north of EastGRIP:

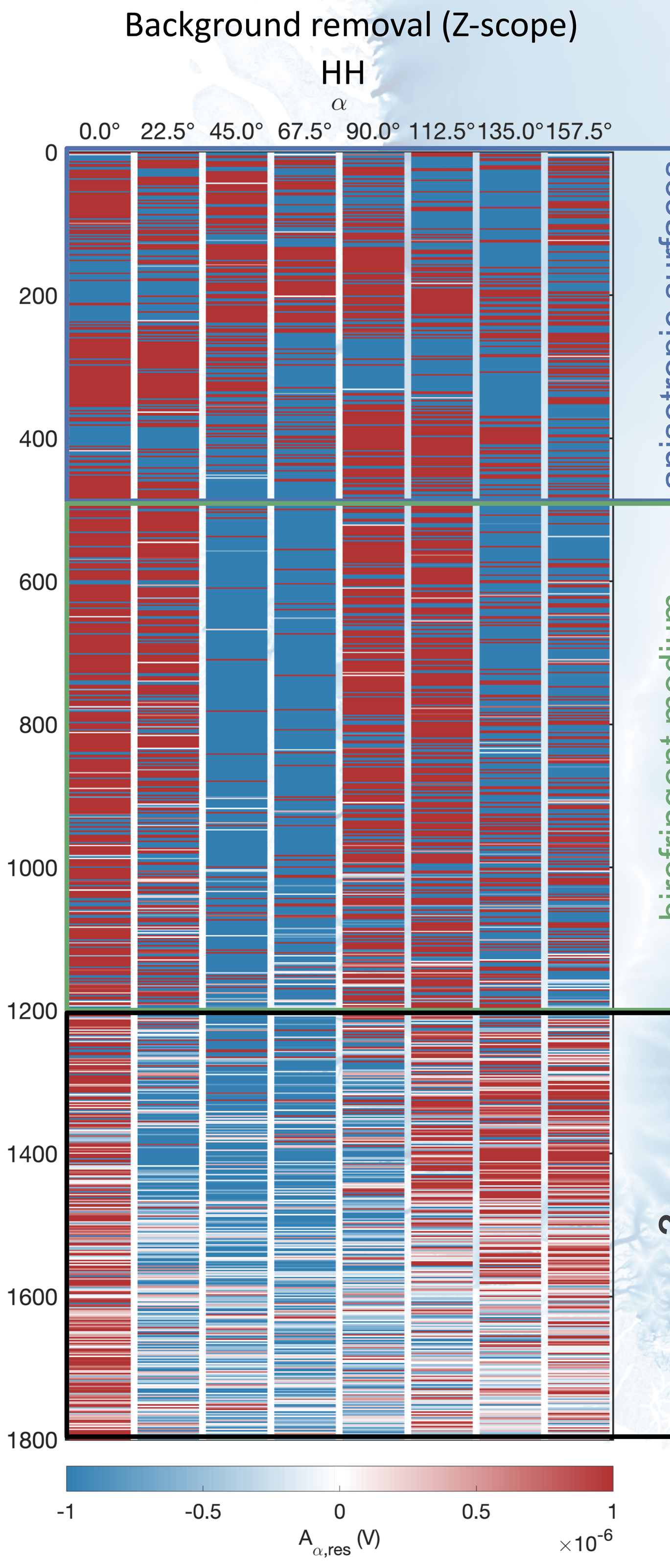
Depth < ~500 m:
HH: 1 maximum detected between 150 – 470 m
HV: 2 maxima detected between 50 – 120 m and 300 – 500 m
- ➢ anisotropic surface
- ➢ indicates a **development** of anisotropic COF

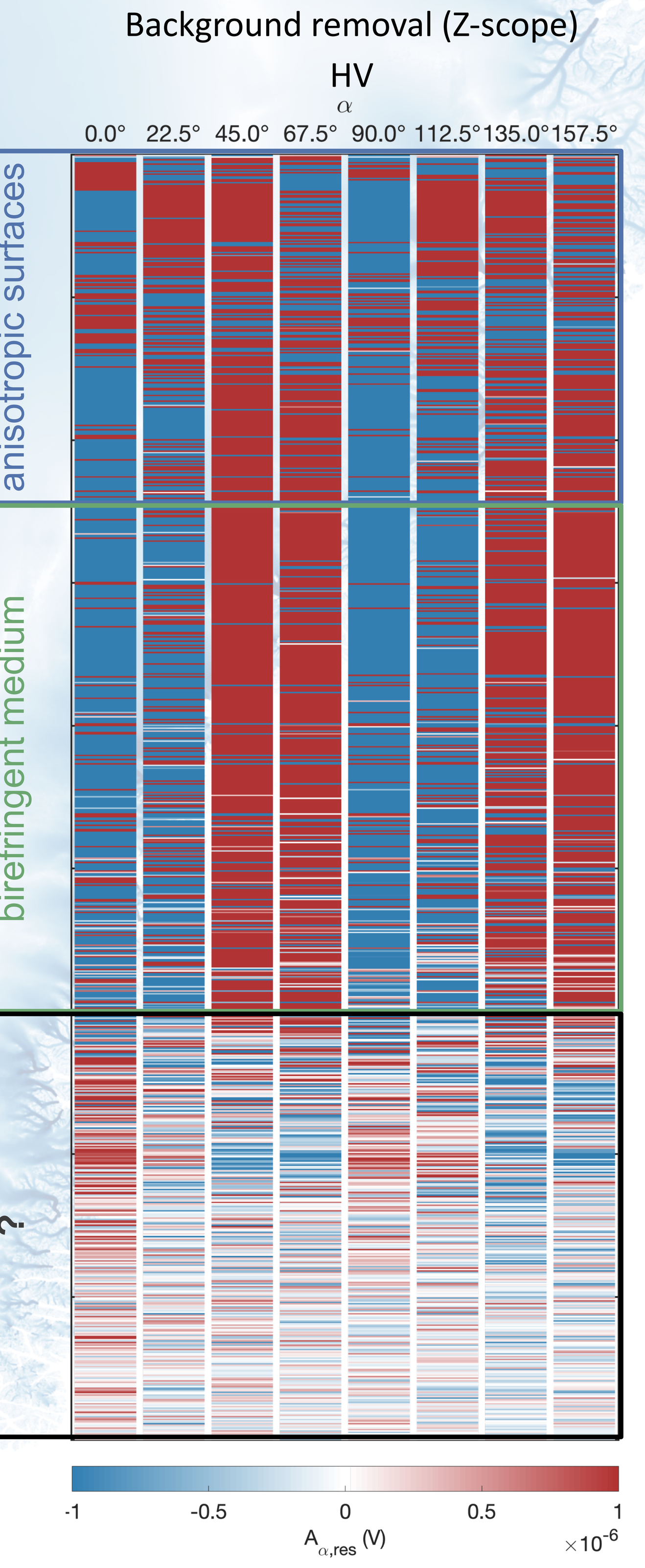
~500 m – ~1200 m:
HH and HV: 2 maxima detected
- ➢ birefringent medium
- ➢ indicates a **constant** anisotropic COF

> ~1200 m:
HH: 1 maximum detected
HV: unclear

EastGRIP





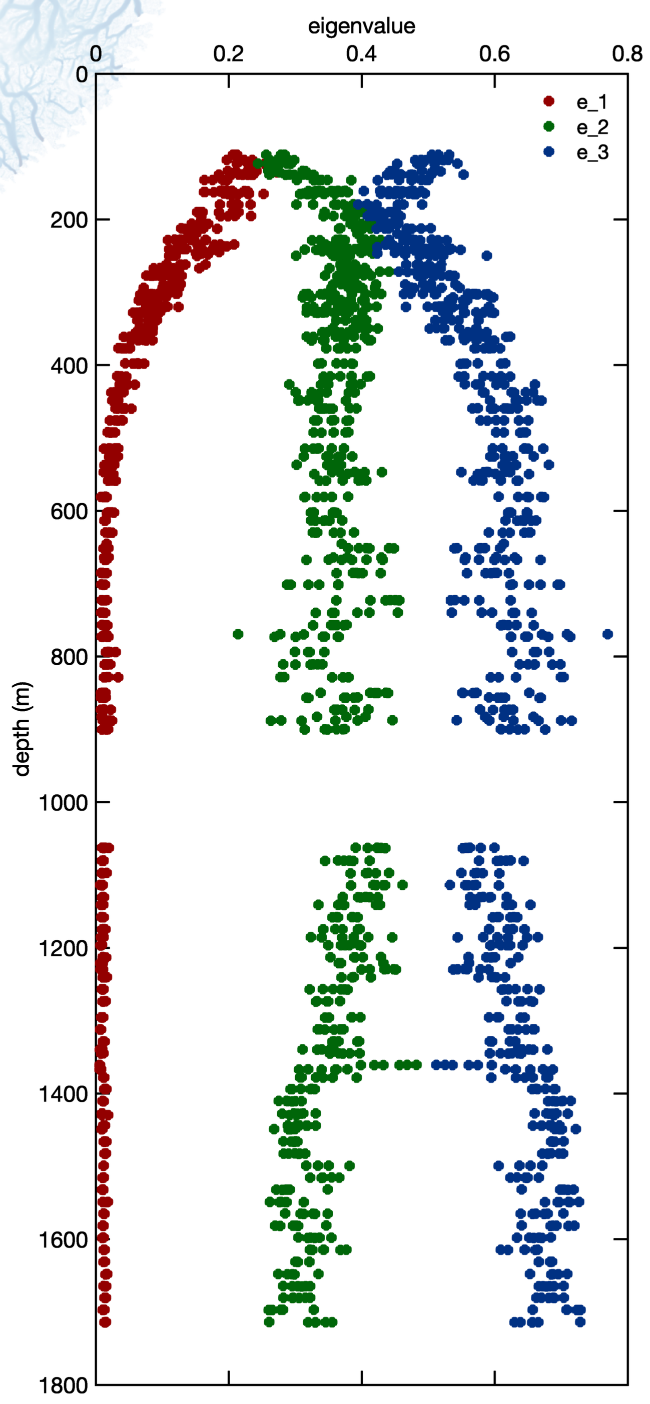


Development of c-axes orientation from ice core:

near surface:
isotropic COF

< ~500 m:
extremely rapid evolution of COF anisotropy

> ~500 m:
stable girdle



(see Stoll (2019))

Results

PpRES measurements indicate a development of anisotropic COF down to a depth of ~500 m. Between ~500 m and ~1200 m, reflections indicate a constant anisotropic COF. From here, HH indicates again a development of anisotropic COF but HV shows no clear pattern. COF derived from ice core thin sections show extremely rapid evolution from isotropic COF to girdle fabric within the upper ~500 m. Below, the girdle is stable.

Conclusion

Observations along the ice core confirms indications from PpRES measurements. As a consequence, the PpRES measurements can be used at other locations to investigate the anisotropy of ice crystals.

Outlook

As a phase-sensitive system pRES also allows to analyze the phases of the received reflections. This will furthermore improve the characterisation of anistropy in ice, e.g. as a function of flow regime and specific geographic settings, independently of ice cores. In 2019, we have performed several measurements in the flowline of EastGRIP to investigate the development of anisotropy around EastGRIP.

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